International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN(P): 2249-6890; ISSN(E): 2249-8001
Vol. 9, Issue 2, Apr 2019, 321-330

TRANS STELLAR
• Journal Publications • Research Consultancy

EFFECT OF GAP CONDITION BETWEEN TWO COMPOSITE PLATES IN BALLISTIC RESISTANCE TESTS

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ABSTRACT

There is a great need to improve the efficiency of bulletproof vests, especially those, which made from composite materials for many reasons including protecting lives of individuals and finding the best materials and arrangements that keeps the environment clean and other technical and economic reasons.

Researches that included the above needs are divided into several topics including development of crystalline structure of the composite materials, studying the use of additives to composite materials or hybrid composite materials, and there are researches on the type of materials used and the number of layers and geometry.

In this work, plates of Kevlar 29/Epoxy with 30, 40 and 60% fiber volume fractionsare manufactured using 4 layers of Kevlar. Samples are assembled from two plates gathered within a frame leaving a gap between them. Three types of samples are used depending on gap condition, the first with free gap, the second kept with pressurized gap, and the third was vacuumed. The pressure level reached ±35 kPa. The samples are exposed to ballistic test with 9mm bullets. The bullet speeds before and after impacts are recorded. It is noticed that 39% speed reduction is gained from the 30% V_f when the sample is pressurized by 35 KPa. This value increased to 42% for V_f 40% about 46% for V_f 60%.

***KEYWORDS:** Composite Materials, Ballistic Test & Bulletproof Vests*

Received: Jan 11, 2019; **Accepted:** Jan 31, 2019; **Published:** Feb 26, 2019; **Paper Id.:** IJMPERDAPR201931

Original Article

1. INTRODUCTION

Bulletproof vests were invented to prevent the vital organs of wearers from injury caused by firearm projectiles. During the past time periods, the armor was developed from different cultures to use it during combat. During the fifth century B.C., a dozen layers of linen were used from Greeks and Persians, while woven coconut palm fiber was used from Micronesian inhabitants of the Gilbert and Ellice Islands until the nineteenth century. In other places, the hides of animals were used as armor: five to seven layers was wore of rhinoceros skin, armor comprised linked rings or wires of iron, steel, or brass it is called Mail armor and wasdeveloped as early as 400 B.C**[1]**.

Composite materials consisting of adhesive materials called matrix and one or more of reinforcing materials such as fibers, particulates or flakes. Increasingly, composite materials have been used in the past decades. The designers used the composite materials in a variety of industries because of high strength, high stiffness and lightweight properties

The composite that consist of continuous fiber, due to its large surface area, the fiber-matrix interface influences the behavior of a composite. Moreover, the matrix providing a mechanism to transfer loads to fibers, the

interface also plays an important role in determining the composite toughness. In spite of many advantages, when the composite materials were compared with commonly used metals, it suffers from lower ductility and toughness **[2]**.

The bulletproof vests became available in a limited manner since the plastics revolution of the 1940s. The vests of the time were made of ballistic nylon and supplemented by plates of steel, fiber-glass, ceramic, Boron, titanium, and the most effective composites of ceramic and fiberglass. Until the 1970s, the standard cloth used for bulletproof vests was Ballistic nylon. In 1965, Kevlar is invented, a liquid polymer that can be spun into aramid fiber and woven into cloth. At the first, Kevlar was developed to use it in tires, and later for such diving products and different parts for planes and boats. 1971, Lester Shubin of the National Institute of Law Enforcement and Criminal Justice advocated to replace bulky ballistic nylon and use Kevlar in bulletproof vests. In 1989, the Allied Signal Company developed a Spectra and competitor for Kevlar.

Polyethylene fiber (originally used for sail cloths) is now used to make lighter, yet stronger, nonwoven material for use in bulletproof vests along-side the traditional Kevlar **[3]**. The development of science helped to use the composite material in the war industry. Composite material, several fibers were used in the armor including carbon fiber, boron fiber, Fiber glass, walnut fiber and others for light weight and flexibility and high resistance to break through. Recently, because of its great advantages of lightweight, flexible, high durability and high tensile strength bulletproof vestsare made from PARA-ARAMID such as polyethylene, spectra, twarone, and Kevlar fibers **[4]**. Kevlar contains a series based on the strong bonding between atoms of carbon rings, where the strength of these rings is five times the strength of steel. For this reason, it's used in protective bulletproof vests. Kevlar is one of the greatest inventions of people working on the distracting strength of trauma to the shot, and absorbs the high kinetic energy smoothly to limit danger that reach the body and save the life of the wearer. The disadvantages of Kevlar like its coast, influence by ultraviolet rays and humidity; push us to use other materials to increase the efficiency, make it resistant to sunlight, and reduce the price and humidity.

2. LITERATURE REVIEW

Many disciplines of researches are held in the field of bulletproof vests improvement. Some of them studied the type of reinforcement materials used like industrial or natural materials and their arrangement;others studied the effect of additives to improve the ballistic properties of vests and few works discussed the effect of change in the crystalline structure of materials used in vests.

Goncalves D.P., et. al. **[5]** used a simple-dimensional mode to analyze the projectiles impact against Ceramic/metal armor. They studied the internal structure and they investigated the effect of grain sized ceramic on the ballistic performance. They concluded that the increase in grin size of the ceramic leads to improve the armor efficiency. Articles **[6 – 9]** involved into improving the ballistic properties of composite materials by using additives. Y. L. Chen et. al. **[6]** used zirconium powder (ZrO_2) as 5% additive to the alumina. M. R. Ahmad et. al. **[7]** added natural rubber as a coating material to the TWARON fabrics. Ramadhan et. al. **[8]** added Alumina powder (Al_2O_3) to Kevlar/Polyester as a development for body armor. C. B. Talicoty **[9]** added walnut shell powder by 5% weight to Epoxy. All the aforementioned research made some improvements in ballistic properties of armors in different percentages.

Most of the researches in the area of ballistic properties improvement interested in the structure of the composite material armor like number of layers, types of materials arrangement in the layers and fiber direction and orientation, numerically, experimental or both. The articles **[10 – 19]** are some of the mentioned type of research. A.H Alhilli **[10]**

studied the energy absorbed from impact of projectiles with fiber reinforced composite materials. He used different matrix materials and different reinforcements. Experimentally, the results show that Kevlar has higher resistance than carbon composites, which in turn is higher than glass fibers. M. Ganesh Babu, et. al.**[11]** used a range of conical projectile speeds (30 – 60) m/sec on (3 and 5) layers and three types of glass fibers. They found that increasing 1 mm thickness increased the ballistic limit near 6 m/sec. Michal Barcikowski **[12]** used different types of E-Glass fiber in ballistic impact test. Cloth, continuous filament and chopped strand mats and two different woven roving are used with polyester. He found that high density of resin and several layers of lightweight fibers enhanced the shock ballistic efficiency, on the contrary of high fiber weight layers without resin enhancement.

J. M. Pereira and D. M. Revilock **[13]** discussed the results of shock response in two materials Kevlar 49 and Zylon. Metal projectiles fired from a gas gun, the initial and final velocity of projectiles (before and after penetration) is recorded. They concluded that on overall weight basis; Zylon can absorb energy more than twice as much as Kevlar. Al-Hamdan A. et. al. **[14]** used 100-1300 m/sec pin projectiles from a gas gun headed to fiber reinforced metal matrix composites. They used Al_{pure} and Al_{6061}as matrix materials. In the conditions of their tests, they found that there is a limiting value for these materials to be useful in armor applications with high-energy impact. D. Dimerki et.al. **[15]** utilized polyethylene woven fabrics, whichare considered the strongest fibers extensively used in ballistic equipment like vests and helmets. Woven fabric composites and unidirectional tapes composites are subjected to ballistic test in the laboratory. The conclusion is that the unidirectional composites suggested showing best performance when compared with bidirectional composites. S. Kumaravel and A. Venkatachalam **[16]** suggested nylon filament yarn combined with carbon nano-tubes as an alternative for Kevlar fabric in bulletproof vests. Y. Regassa et. al. **[17]** studied armors made from Kevlar-29/polyester. They discussed the number of layers and they suggested a 20 layer Kevlar-29/polyester is capable to stop a 7.62*39 mm built shot from a distance of 10m and speed of 720 m/s. Sujith N. S. et. al **[18]** made a numerical study with ANSYS-14 on various materials traditionally used in bulletproof vests. The study indicated that SPECTRA 900 fibers have best results compared to Kevlar-149 and Boron fibers with minimum stress and deformation after impact. Ehsan S. Al-Ameen, et. al. **[19]** used different arrangements of fiber reinforced composites made from Kevlar29, E-Glass (Mat and random) with Epoxy matrix material. They suggested using two plates of the composite materials with a gap in between. Titanium dioxide powder is added to the matrix with 2% wt fraction. They found that the samples with gap presence gained about 20% energy absorption from the samples without gap.

In this work, the arrangements of two composite plates with a gap in between, with different gap conditions are discussed for the influence of these conditions on the armor efficiency. Kevlar 29/Epoxy composite plates are used with4pliesof Kevlar Mat and 40% volume fraction. The plates areexposed to ballistic tests by means of fired bullets. Theabsorbed Kinetic Energy at plate penetration is measured. Three different conditions are applied, free air gap, vacuumed gap and pressurized gap.

3. EXPERIMENTAL WORK

The test rig is shown in **figure (1)** and consists of the following:

- Target: The targets are the plate samples, which are 21 cm square shaped and 2 mm thick as shown in **figure (2)**. An aluminum frame is used as a fixture for the two plates which are 10 mm apart.
- 9 mm handgun: used to shoot the bullets on the target.

- Velocity measurement device: two (chronographs) are used to detect the bullet speed before and after hitting the target. **Figure (3)** shows the chronograph.

Figure 1: The Test Rig

Figure 2: The Target Sample

Figure 3: Chronograph

Hand layup process is used to make the samples from Kevlar 29 mat **figure (4)** and Epoxy **figure (5)**. **Table 1** gives the mechanical properties of the materials. The bullet net mass is 8 gm and the initial velocity is 350 m/s.

Figure 4: Kevlar Mat

Figure 5: Epoxy

The target platesamples are made of four plies of Kevlar with three different volume fractions 30, 40 and 60%.

Three conditions for the plates' arrangement are used; the first is when the two plates are fixed without any effect in the gap between them. The second case, when the gap is pressurized from 0 to 35 KPa and the third case, when the gap is vacuumed from 0 to -35 KPa. The maximum pressure value is limited to 35 KPa to avoid any failure in the samples due to the deflection of the plates.

Table 1: The Mechanical Properties of the Materials used in this Work

Materials	Density (Kg/m^3)	Young's Modulus (GPa)
Kevlar	**1180**	**36**
Epoxy	**1100**	**1.06**

Equation 1 gives the Kinetic Energy for the bullet. Equation 2 gives the absorbed kinetic energy during the target penetration.

$$KE_{abs} = \frac{1}{2}mv^2 \quad (1)$$

$$KE_{abs} = \frac{1}{2}m(v_1^2 - v_2^2) \quad (2)$$

Where:

$\boldsymbol{KE_{abs}}$ **:** The absorbed energy

$\boldsymbol{m}$ **:** The mas of bullet

$\boldsymbol{v_1^2}$ **:** The initial velocity of bullet

$\boldsymbol{v_2^2}$ **:** The final velocity of bullet

Several cases are tested in this work. The first case was the 30% volume fraction free air gap test, by shooting the target from five meters distance [20]. The test is repeated for the 40% and 60% volume fraction samples. Three values for each test are recorded and the average value for each test is reported.

The above procedure is repeated for the cases with pressurized gap condition while the pressure increased within the range mentioned earlier. Again, the procedure is repeated for the case of vacuumed gap condition.

4. RESULTS AND CONCLUSIONS

The average values of the final velocity for the free air gap condition are shown in table 2. The results for the pressurized cases are shown in figures (6, 7 & 8) and those of the vacuumed condition are in figures (9, 10 & 11).

Table 2: The Final Bullet's Velocity for the Free Air Gap Samples

Volume Fraction %	Final bullet's Velocity (m/s)	Absorbed Kinetic Energy (J)
30	261	212
40	249	242
60	225	289

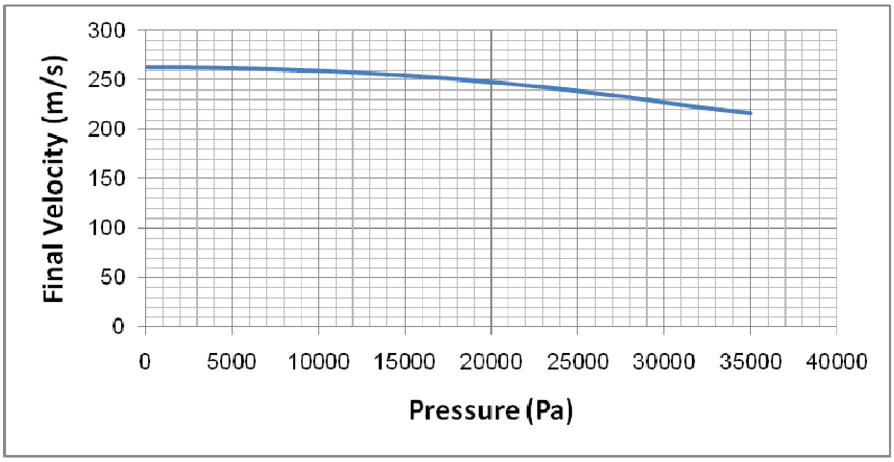

Figure 6: Pressure - Final Velocity for Pressurized Sample (V_f= 0.3)

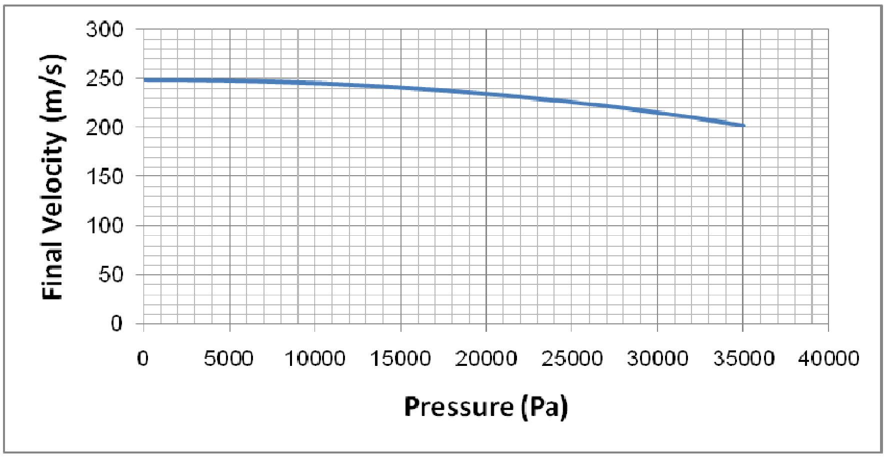

Figure 7: Pressure - Final Velocity for Pressurized Sample (V_f =0.4)

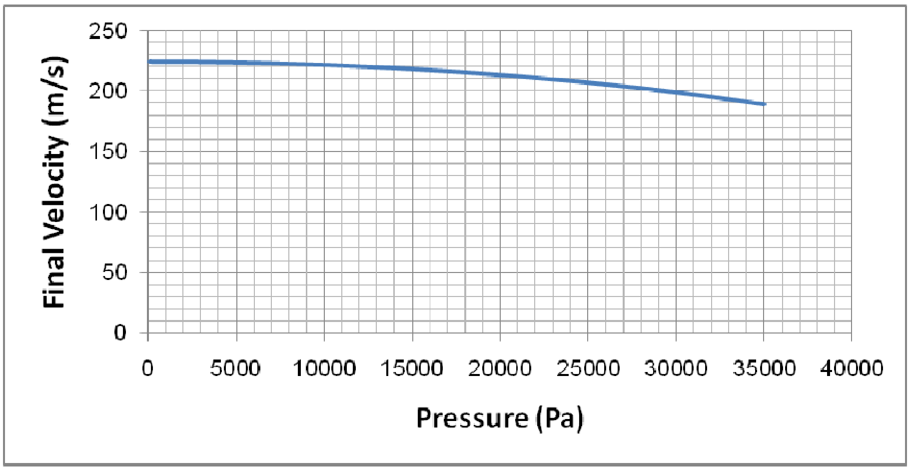

Figure 8: Pressure - Final Velocity for Pressurized Sample (V_f = 0.6)

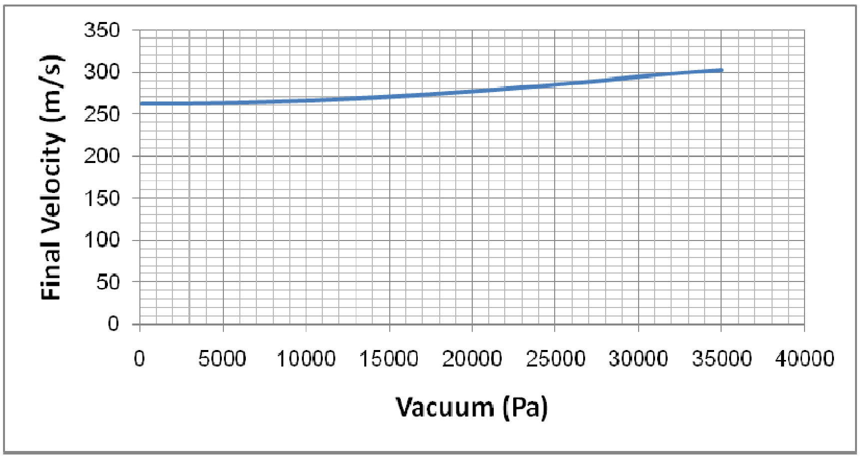

Figure 9: Pressure - Final Velocity for Vacuum Sample (V_f= 0.3)

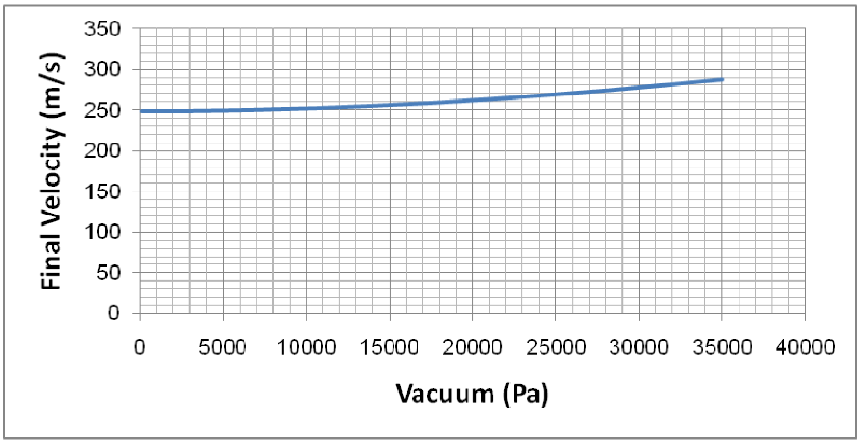

Figure 10: Pressure - Final Velocity for Vacuum Sample (V_f =0.4)

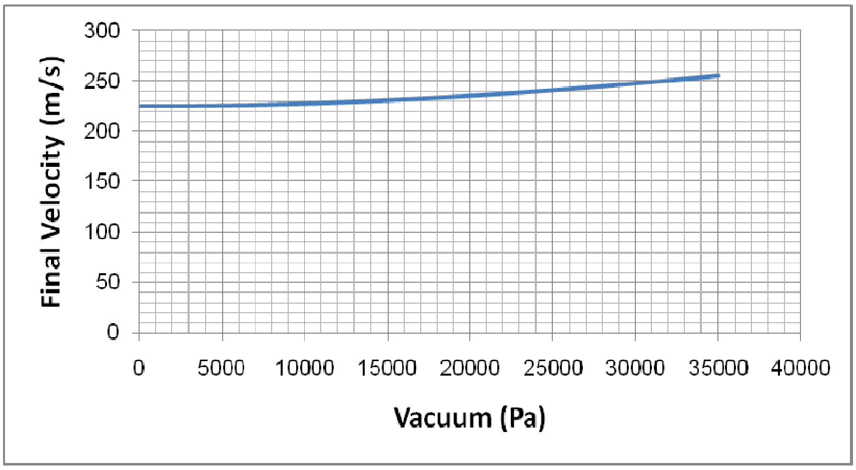

Figure 11: Pressure - Final Velocity for Vacuum Sample (V_f = 0.6)

From the above results, it is noticeable that the effect of the pressure between the plates increases the ability to withstand the bullet by the target. On the contrary, in the vacuumed case, the effect of the vacuum with the same pressure level decreases the target efficiency.

For the first case, i.e. the free air gap samples, the 30% V_f plates reduced the bullet's speed about 25.5%.

This reduction increased to about 29% for the 40% V_f and 36% for the 60% V_f samples. In other words, increasing 10% of fiber volume fraction gained 3.5% decrease in bullet speed. It can be noticed from figure (6), that 39% speed reduction is gained from the 30% V_f when the sample is pressurized by 35 KPa. This value increased to 42% for V_f 40% as shown in figure (7) and about 46% for V_f 60% as in figure (8).

Finally, it can be concluded that the roll of pressure is to increase the ability of the target to endure the bullets, and it can be a method to reduce the cost of vests. The pressure in the gap may be replaced by other mechanical load, which pre-stresses the vest plates to endure the bullets.

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